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June 5, 1961

XEROX

Bureau of Naval Weapons
Department of the Navy
Washington 25, D. C.

Attention: RRMA-231

Via: Inspector of Naval Material
10 North 8th Street
Reading, Pennsylvania

Subject: Bureau of Naval Weapons, Department of the Navy
Contract NOw 61-0410-c
Ultrasonic Welding of Refractory Metals
Bimonthly Progress Report No. 1

Reference: Contract NOw 61-0410-c
Item 2

Gentlemen:

In accordance with the referenced contract, this letter constitutes the first bimonthly progress report covering the work done during the period March 1 through April 30, 1961 on the referenced contract.

The objective of this program is the investigation of the ultrasonic welding machine settings required and evaluation of properties of the welds obtainable for the following refractory metals or alloys:

1. niobium-10% molybdenum-10% titanium, Nb-10 Mo-10 Ti

2. molybdenum-0.5% titanium, Mo-0.5 Ti

3. tungsten.

These three metals were chosen for investigation because their temperature-strength properties are particularly attractive.

Effort during this period established sources for initial quantities of the refractory sheet metals, modified spot-welding equipment to accommodate the range of parameters anticipated with these metals, and produced preliminary data related to the welding energy and clamping force requirements for one of the alloys being studied (molybdenum-0.5% titanium).

BACKGROUND

Efforts to join refractory metals and alloys by fusion-welding processes have been but partially successful, particularly with those metals exhibiting negligible room-temperature ductility, such as molybdenum and tungsten. Both of these metals are embrittled when recrystallized, but undergo a brittle-to-ductile transition within intermediate-temperature ranges. A primary deficiency of a fusion weld in these materials is the loss of ductility within the recrystallized zone surrounding the crystallized weld metal.

Ultrasonic welding offers a potential solution to this problem since it is a solid-state-bonding technique. Although local heating of the contact surfaces does occur, the magnitude of the temperature rise has been shown (1) generally to be only 35-50% of the homologous melting temperature. This temperature rise would be sufficient, in the case of molybdenum and tungsten, to achieve bonding above the transition temperature and to take advantage of the increased ductility. The resulting joints would be expected to be ductile, since complete recrystallization and contamination by interstitials are suppressed.

The current work is limited to those gages (up to 0.025 in.) which are expected to be weldable within the power capacity of spot-welding equipment presently available in our laboratories.

MATERIALS

Information on the availability and physical properties of the three materials of interest (Nb-10 Mo-10 Ti, Mo-0.5 Ti, and tungsten) was obtained. A pilot quantity* (ranging from a few square inches of one gage to 2 sq ft of another) of each material in the gages of interest to the project was ordered and was received at the end of this reporting period. The physical and mechanical properties of the material received are tabulated in Table 1. Data for the gages of interest, particularly of tungsten, are scarce.

The Nb-10 Mo-10 Ti purchased from duPont is their Alloy D31 in which the carbon content has been reduced from approximately 1000 ppm to 60-100 ppm in order to raise its embrittlement temperature (short-time exposure) from 2500°F to 2900°F. Although temperatures in the range of 2500°F to 2900°F will not be reached during ultrasonic welding, determinations will be made of the temperature rise in the weld zone during welding. In view of the limited information now available on tungsten, it is expected that it will be the most difficult to weld. Further pertinent information on the properties and characteristics of these metals will be reported as obtained during welding, from the literature, and from other outside sources.

WELDING MACHINE SETTINGS

Before the materials ordered were received, preliminary welding was done on some 0.006- and 0.011-in. Mo-0.5 Ti sheet taken from residual stock from previous work. The history of this material is unknown, but it was laminar in character as observed during shearing of the test coupons, sharp bending, and peeling of weldments.

(1) Aeroprojects Incorporated, "Fundamentals of Ultrasonic Welding, Phase II", RR-60-91, Final Report on Navy Contract NOas 59-6070-c, Aug 1960.

* These refractory metals range in price from $50 to $150 per lb in the gages desired.

Table 1

SUMMARY OF DATA ON THREE REFRACTORY METALS PURCHASED
(All data are room-temperature data furnished by the manufacturer unless otherwise specified.)

Alloy	Nb-10 Ti-10 Mo	Mo-0.5 Ti*				Tungsten
Manufacturer	duPont	Universal Cyclops Steel Corp.				Fansteel Metallurgical Corp.
Description	Modified to contain 60-100 ppm carbon instead of 1000 ppm**	Hot-rolled from ingots made by consumable-electrode, vacuum-arc process; stress-relieved; descaled				Rolled from ingots produced by powder-metallurgy technique
Gages Purchased, in.	0.008, .010, .015, .020	0.005		0.010		0.005 0.010
Amount, sq ft	1 (total)	1		2		1 1
		T#	P#	T#	P#	For Gages of 0.010- to 0.040-in.
Ultimate Tensile Strength, psi	100,000 45,000 at 1850°F	153,000	140,700	158,000	140,200	120,000-300,000
Yield Strength, psi		140,000	126,800	125,700	106,300	
Modulus of Elasticity, psi	16.3×10^6					
Elongation, %		6.5	12.5	8.5	13.5	
Vickers Microindentation Hardness No.	238-246##	265## 269##	272	279 269##	279	390-460##
Embrittlement Temp, °F	2900					
Ductile-Brittle Temp, °F						400-1000
Recrystallization Temp, °F (1 hr in vacuum)	For Gages, in. 0.010: 1875 0.030: 1910					

* Each item of manufacturer's quantitative data is the average of two specimens except transverse UTS for 0.005-in. which represents a single value.
** To raise embrittlement temperature (short time exposure) from 2500°F.
# Determined on planes normal to the rolling plane and in directions transverse (T) and parallel (P) to the rolling direction.
Determined at Aeroprojects.

The Vickers microindentation hardness number was found to be 230 for the 0.006-in.-thick and 260 for the 0.011-in.-thick sheets.

Power and Welding Interval

Previous work (1) resulted in the following empirical formula which predicts, for most metals, the approximate electrical energy into magnetostrictive transducers required to accomplish ultrasonic welding:

$$E = 316\, H^{(1.5)}\, t^{(1.5)}$$

where

E = electrical energy (supplied to the transducers of the spot welding machine), watt-seconds

H = Vickers microindentation hardness number

t = thickness of the material adjacent to the sonotrode tip, inches.

Consequently, the predicted approximate energy requirements for the 0.006-in. and 0.011-in. Mo-0.5 Ti was calculated to be 500 watt-sec and 1500 watt-sec, respectively.

From this equation was estimated the minimum electrical energy required to weld each of the three refractory alloys in the gages of interest; the data are given in Table 2. Our previous experience indicated that to obtain a good ultrasonic weld in a hard material, especially one of low ductility in the intermediate-temperature range, usually requires that the welding interval be short (a fraction of a second). Therefore, the power requirements for the calculated energies have been calculated for welding intervals of 0.2, 0.3, and 0.5 sec and are also reported in Table 2. These calculated data augment our previous predictions of difficulty in ultrasonically welding tungsten. The degree to which the three metals conform during experimental welding to the predictions of Table 2 will be routinely reported.

Determination of Proper Clamping Force to Effect a Best Impedance Match

It has been established (1) that for each thickness of material, a power and clamping force relationship exists which minimizes the power required to accomplish an ultrasonic weld between two sheets. There are several methods by which this machine setting can be determined.

One technique, which can be used when dealing with reasonably malleable materials, consists of arbitrarily selecting a single clamping-force setting and a fixed welding interval and welding at progressively decreasing power until the bond obtained no longer fails in peel by nugget tearout. The procedure is repeated at other clamping-force settings until sufficient data are obtained to produce a plot of power vs clamping force which is a concave-

Table 2

ELECTRICAL ENERGY AND POWER REQUIRED FOR ULTRASONIC WELDING OF
THREE REFRACTORY METALS CALCULATED
ON BASIS OF ENERGY:HARDNESS:THICKNESS EQUATION

			Required to Weld			
			Electrical Energy,	Power (for indicated Time), watts		
Metal	Gage, in.	Hardness, VHN*	watt-sec	0.3 sec	0.5 sec	0.8 sec
Nb-10 Mo-10 Ti	0.005	250	420	1,400	840	525
	.008	246**	870	--	--	--
	.010	269**	1,100	3,660	2,200	1,375
	.015	238**	2,200	--	--	--
	.020	240	3,200	10,650	6,400	4,000
	0.025	240	4,600	--	--	--
Mo-0.5 Ti	0.005	269**	500	1,665	1,000	625
	.010	269**	1,450	4,830	2,900	1,810
	.020	270	4,000	13,320	8,000	5,000
	0.025	270	5,400	--	--	--
Tungsten	0.005	390**	850	2,830	1,700	1,065
	.010	458**	3,000	10,000	6,000	3,750
	.020	450	8,500	28,300	17,000	10,625
	0.025	450	11,500	--	--	--

* Microindentation Vickers hardness number.

** Hardness values measured at this laboratory; other values estimated.

upward threshold curve for welding. It appears (2) that the minimum point on this concave-upward curve corresponds to the condition of best impedance match into the weld zone.

For brittle materials such as tungsten, the nugget pullout test is clearly not feasible, and it is anticipated that this will also be true of the thicker gages of Mo-0.5 Ti and duPont D31 alloy. However, it has also been shown (1) that, for any fixed and reasonable value of vibratory power (even though the power level may be too low to produce an actual weld), the temperature rise in the intended weld locale is maximum within the clamping force range associated with the minimum power (that is, the minimum value of the power-clamping force threshold curve previously described). Thus, for brittle materials, a convex-upward curve of temperature rise in the weld locale vs clamping force can be obtained.

Both of these techniques were used in preliminary evaluation of the powder-metallurgy Mo-0.5 Ti sheet.

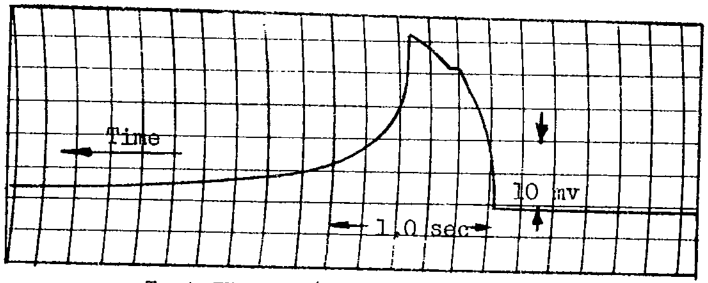
Measurement of Temperature Rise in the Weld Zone

Coupons of 0.011-in. Mo-0.5 Ti were "sensed" in the weld zone with No. 40 gage constantan thermocouple wire. The thermocouple junction consisted of the coupon, and a single constantan wire potted into the zone of the intended weld. Each coupon was welded to itself, effecting a monometal weld between the coupon and a bimetal thermocouple junction with the wire. The output was recorded with a Brush d-c amplifier and strip-chart oscillograph.

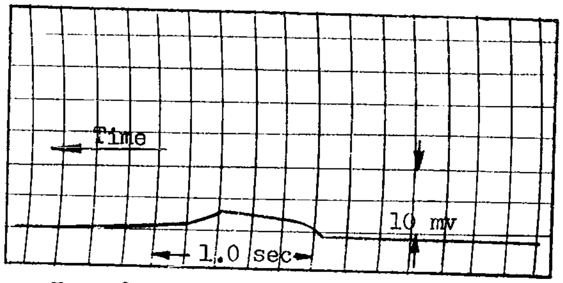
There was difficulty with erratic temperature-rise traces in various specimens, due in part, to the tendency of the sheet to delaminate during spot welding as mentioned earlier. Consequently, only those readings were considered valid which exhibited smooth rise and decay curves as illustrated by the sample traces in Fig. 1.

Figure 2 is a plot of the temperature-rise values, as a function of clamping force, that were obtained. In every case, the power level was 1200 watts to the transducers, applied for 0.6 sec. The sonotrode tip was made of Astroloy (discussed on p. 12) machined to a 3-in. spherical radius. The straight line was determined by statistical analysis carried out under the assumption that the temperature varies inversely and linearly with the clamping force. Actually, the true curve would be nonlinear, convex-upward, with a maximum temperature rise occurring at some intermediate value of clamping force. However, since, at the time of this scouting study, clamping

(2) Aeroprojects Incorporated, "Fundamentals of Ultrasonic Welding, Phase I", RR-59-105, Final Report on Navy Contract NOas 58-108-c, May 1959.



Test 7D: 375-lb Clamping Force



Test 8R-H: 700-lb Clamping Force

Fig. 1: TYPICAL TEMPERATURE TRACES

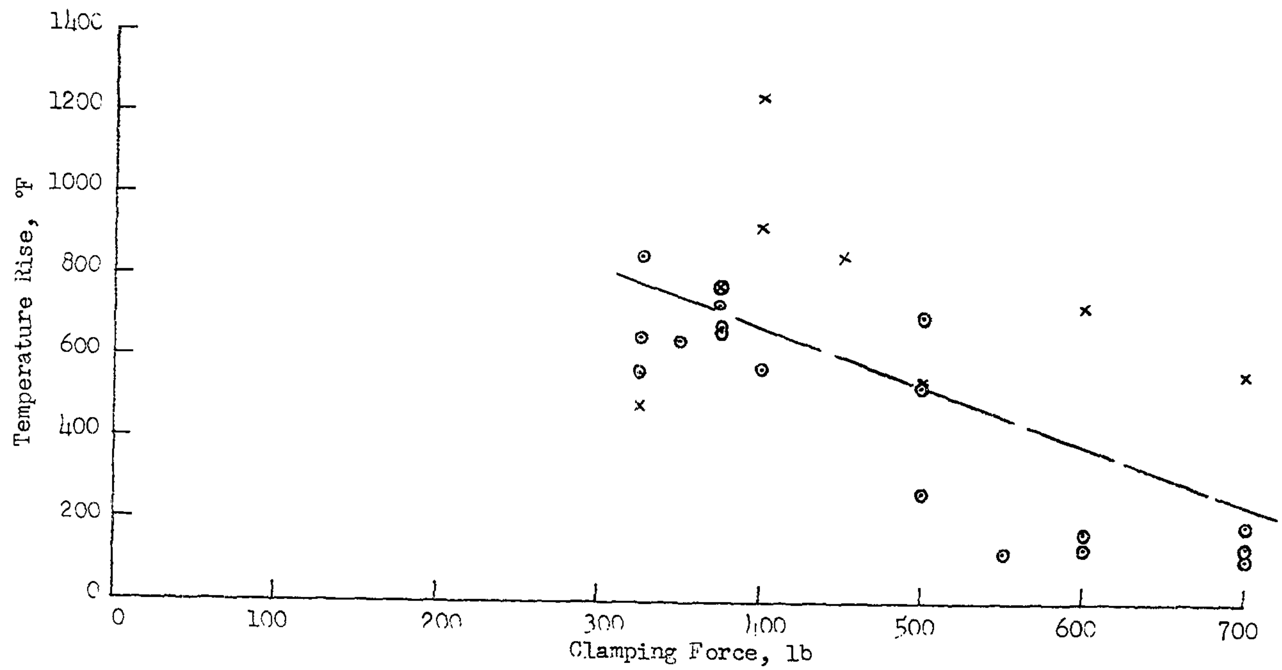


Fig. 2: TEMPERATURE RISE IN THE WELD ZONE AS A FUNCTION OF CLAMPING FORCE DURING ULTRASONIC WELDING OF 0.011-INCH POWDER-METALLURGY MOLYBDENUM-0.5% TITANIUM ALLOY

Astroloy Sonotrode Tip: 3-in. spherical radius
Power (marginal for welding): 1200 watts
Welding Interval: 0.6 sec

x First weld pulse on a specimen
⊙ Pulse subsequent to initial weld (clamping force not removed)

forces lower than 325 lb could not be accurately measured with the welder used, the desired clamping force was not definitely established. (The machine has since been modified so that clamping force can be set accurately at any value from 50-1000 lb.) It is evident from Fig. 2, nevertheless, that the optimum force is at or below the 300- to 400-lb region, not above it.

Estimation of Threshold Curves By Weld Peeling

As a check on the temperature-rise method for determining the clamping force for a best impedance match, the nugget peel test described earlier was also utilized on welds of 0.006- and 0.011-in. Mo-0.5 Ti (residual stock material). The nugget peel test is a quasi-quantitative technique in which welds, produced at various conditions of energy and clamping force, are qualitatively evaluated by manual peeling and graded as follows:

a. Excellent weld (nugget pulled from one of the sheets, encompassing the entire weld envelope)

b. Moderate weld (nugget pulled from only a portion of the weld envelope)

c. Partial bonding (sticking, but no true weld)

d. No bonding.

Figures 3 and 4 are the threshold curves determined in this manner for the 0.006-in. and 0.011-in. material respectively. Figure 4 confirms the indications of Fig. 2, namely, that the optimum clamping force for 0.011-in. sheet is, in fact, in the region of 300 to 400 lb. Oddly enough, Fig. 3 indicates the same range of force for the 0.006-in. sheet, which does not appear to agree with earlier experience that the optimum clamping force increases with thickness. No explanation can be offered for this observation at this time.

These tests will be repeated on the arc-cast Mo-0.5 Ti which has now been received.

SONOTRODE TIP MATERIALS

The dynamic stresses associated with the delivery of ultrasonic energy during welding of high-strength or hard metals and alloys imposes severe requirements on the terminal tips of the sonotrodes.

Ordinary tool steels give satisfactory performance and life in welding aluminum or copper alloys, and Inconel X has given equally good performance for welding mild steels, titanium, zirconium, and other soft or low-melting alloys. In attempting to weld high-strength, high-temperature, and hard, brittle metals and alloys, however, tip life with the tool steels is short, sometimes less than 10 welds per tip; Inconel X is somewhat better but in some circumstances probably is not suitable for production welding.

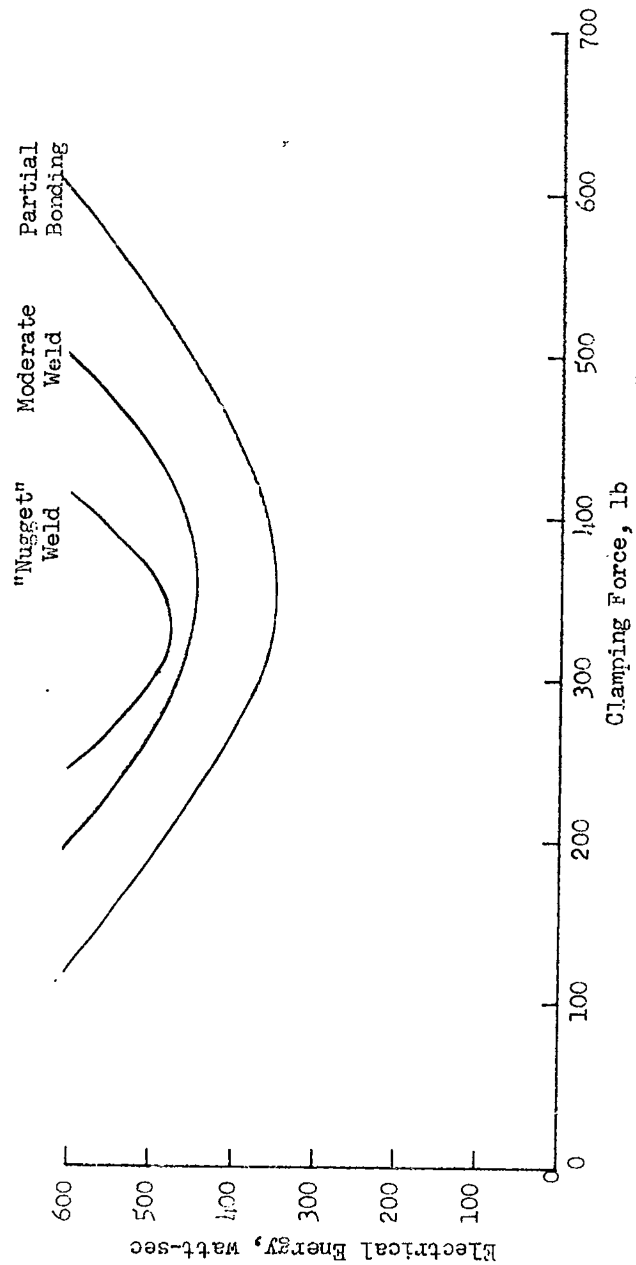


Fig. 3: ULTRASONIC WELDING THRESHOLD CURVES, ENERGY-CLAMPING FORCE, FOR 0.006-INCH MOLYBDENUM-0.5% TITANIUM ALLOY (Powder Metallurgy)

Astroloy Sonotrode Tip: 3-in. radius

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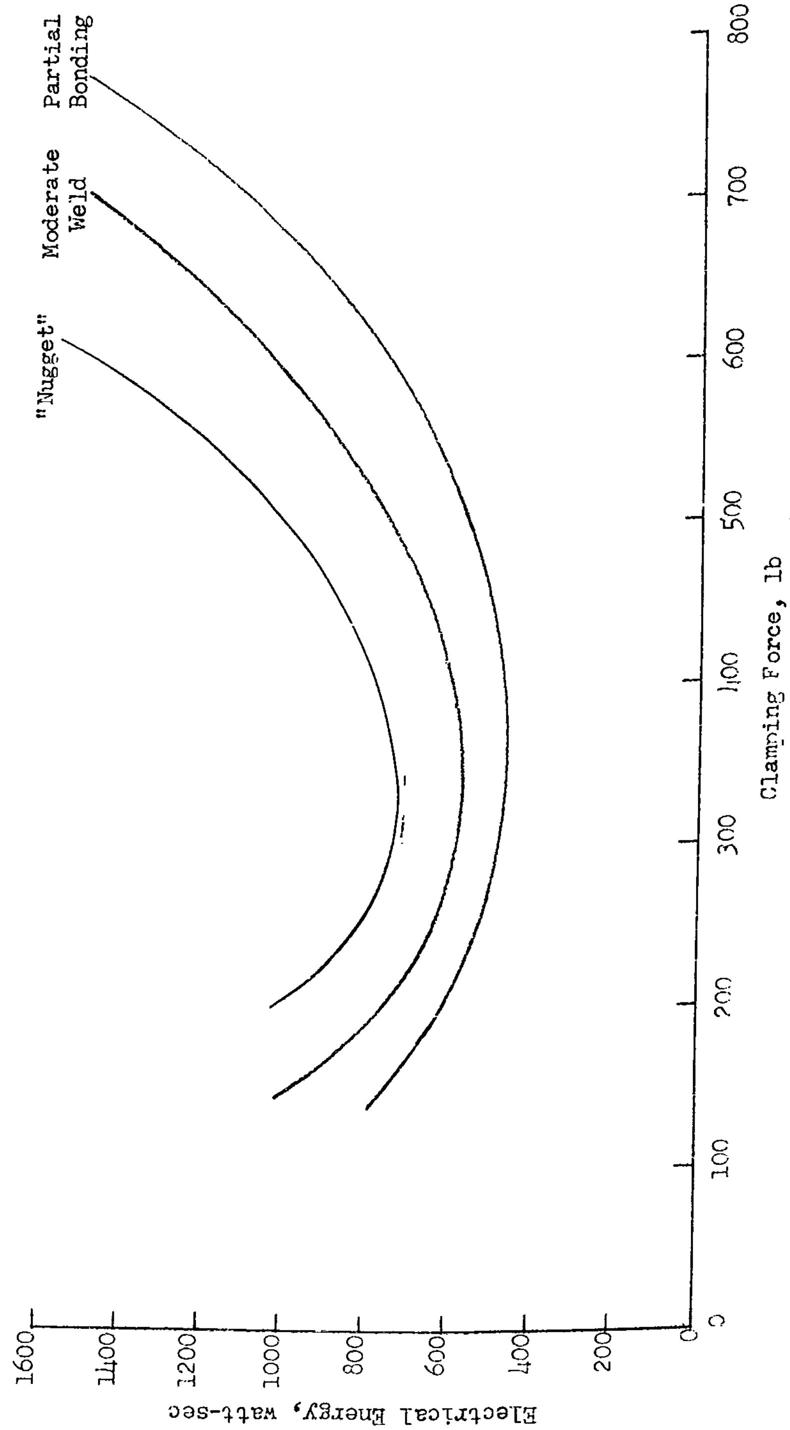

Fig. 4: ULTRASONIC WELDING THRESHOLD CURVES, ENERGY-CLAMPING FORCE, RELATIONSHIP, FOR 0.011-INCH MOLYBDENUM-0.5% TITANIUM (Powder Metallurgy)

Astroloy Sonotrode Tip: 3-in. radius

Tips made of a relatively new nickel-base alloy (Astroloy*), possessing superior high-temperature creep properties, have exhibited long life and excellent welding characteristics for welding various high-strength, hard materials such as beryllium and full-hard stainless steel. All of the work with the materials of interest has been done with machined 3-in.-spherical-radius Astroloy tip on the active sonotrode. Additional tips are now being fabricated from this alloy. Its performance and that of other experimental tip materials, if necessary, will be reported as such information is accumulated in the course of the work.

FUTURE WORK

For the next report period, the work planned includes:

1. Exploratory welding to determine machine variables will be carried out on the three metals of interest: D-31, Mo-0.5 Ti, and tungsten.

2. Based on the energy required to weld as determined from these experiments, additional quantities of each metal will be ordered, including the maximum gage predicted to be weldable with existing spot-welding equipment.

3. Evaluation of weld properties will be undertaken as success in welding permits.

Very truly yours,

C R Frownfelter

C. R. Frownfelter
Senior Engineer-Staff
Assistant

CRF:nj

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* Product of the General Electric Co.